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NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California 93043

Expendable Doppler Penetrometer For Deep Ocean Sediment Strength Measurements

BY
R.M. BEARD

MARCH 1984

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DEEP OCEAN
TECHNOLOGY PROGRAM

METRIC CONVERSION FACTORS

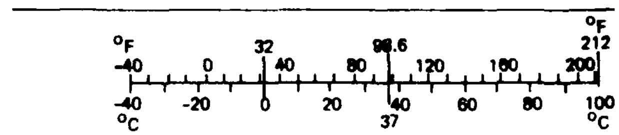
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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An expendable dynamic penetrometer has been developed to measure seafloor penetrability and undrained shear strength at water depths to 6,000 meters (20,000 feet). The penetrometer weighs 1.4 kN (315 pounds) and is 2.3 meters (7.5 feet) long and 90 mm (3.5 inches) in diameter. Data on the velocity of the penetrometer as it penetrates the seafloor are acquired by a Doppler instrumentation system. A 12,000-Hertz

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20. Continued

constant frequency sound source is mounted on the penetrometer. As the penetrometer moves away from a support ship, the signal frequency received at the ship is different than that transmitted by the moving penetrometer's sound source. This change is the Doppler effect. The signal frequency change, an analog of the penetrometer's velocity, is monitored at the support ship and recorded for analysis. The analysis is done on a microcomputer with interactive data processing programs. The output of the program is an undrained shear strength profile. The results of tests in pelagic clays, calcareous oozes, and various types of terrigenous sediments are presented and compared to conventionally acquired strength data. It is concluded that the penetrometer is operable to 6,000-meter (20,000-foot) depths and will penetrate 9 meters (30 feet) into soft seafloors, that good estimates of undrained shear strength can be acquired with the penetrometer, and that the system components are reliable.

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An expendable dynamic penetrometer has been developed to measure seafloor penetrability and undrained shear strength at water depths to 6,000 meters (20,000 feet). The penetrometer weighs 1.4 kN (315 pounds) and is 2.3 meters (7.5 feet) long and 90 mm (3.5 inches) in diameter. Data on the velocity of the penetrometer as it penetrates the seafloor are acquired by a Doppler instrumentation system. A 12,000-Hertz constant frequency sound source is mounted on the penetrometer. As the penetrometer moves away from a support ship, the signal frequency received at the ship is different than that transmitted by the moving penetrometer's sound source. This change is the Doppler effect. The signal frequency change, an analog of the penetrometer's velocity, is monitored at the support ship and recorded for analysis. The analysis is done on a microcomputer with interactive data processing programs. The output of the program is an undrained shear strength profile. The results of tests in pelagic clays, calcareous oozes, and various types of terrigenous sediments are presented and compared to conventionally acquired strength data. It is concluded that the penetrometer is operable to 6,000-meter (20,000-foot) depths and will penetrate 9 meters (30 feet) into soft seafloors, that good estimates of undrained shear strength can be acquired with the penetrometer, and that the system components are reliable.

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INTRODUCTION

This report describes an expendable dynamic penetrometer for measuring seafloor penetrability and undrained shear strength at water depths to 6,000 meters (20,000 feet). The components of the penetrometer are described, procedures for its use are given, and a method for determining soil strength from penetrometer data is presented. In addition, the results of penetrometer tests in seafloor sands, clays, and oozes are presented. Shear strength results derived from the penetrometer data are compared to other in-situ or laboratory shear strength data. The objective in developing the dynamic penetrometer was to provide an expedient means for determining seafloor characteristics and properties relevant to site selection and design of embedded plate anchors. This work was managed by the Naval Facilities Engineering Command under the Deep Ocean Technology Project of the Naval Sea Systems Command.

BACKGROUND

Proper design of systems founded on, anchored to, or penetrating the seafloor requires information on geotechnical properties of the seafloor. The difficulty and cost of acquiring geotechnical properties increase as water depth increases and weather and sea conditions deteriorate.

The mainstay in seafloor geotechnical surveys is coring, which is time-consuming and limited to fair weather. The time needed for taking a core is largely a function of water depth, but 4 to 6 hours is typical in deep water. Limiting weather conditions are a function of vessel size, corer size, and other factors but can be approximately defined by sea state 4. These factors have led to efforts to develop an expedient and less weather-dependent tool for measuring geotechnical properties.

The most promising concept has been the dynamic penetrometer. In this concept, an instrumented probe penetrates into the seafloor, and provides information on the motion of the penetrator during the penetration event. These data are analyzed with a mathematical model describing penetration phenomenon to determine a soil strength profile over the depth of penetration.

One of the first tools using the concept of a dynamic penetrometer to measure seafloor characteristics was reported by Robertson (1965). A device similar to an expendable bathythermograph was developed as a soil-bearing meter. The device was small and lightweight; consequently, penetration was limited to a few feet in soft sediment. Scott (1970) reported on a mechanical accelerometer for use with an ocean penetrometer or corer to obtain penetration records. The device was lowered near the seafloor, where a standard corer tripping system allowed it to

free-fall the remaining distance to the seafloor. Sandia Laboratories began development of a seafloor penetrometer in 1970 (Colp et al., 1975). Two penetrometer designs were tested under this program. One was 1.3 meters (4.2 feet) and the other was 1.5 meters (5.0 feet) long. Both were 76 mm (3 inches) in diameter, had a mass of 45 kg (3.1 slugs), and used a trailing electrical wire to transmit accelerometer data to a surface support craft.

The Navy's initial interest in a dynamic penetrometer resulted from the application of propellant-embedded anchors in the deep ocean (Beard, 1976 and Beard, 1977). Geotechnical data requirements for these anchors were sediment strength and penetrability to soil depths of 9 meters (30 feet) in water up to 6,000 meters (20,000 feet) deep. Based on the work of True (1975), it was concluded that soil data gathered with a penetrometer would be suitable for estimating fluke penetration and short-term anchor holding capacity.

To achieve a penetrometer operable to the 6,000-meter (20,000-foot) water depth that was also expedient required special consideration of the instrumentation used to measure the body motions of the penetrometer. Previously used systems (Robertson, 1965; Scott, 1970; Colp et al., 1975) were inappropriate. The systems reported by Robertson and Colp required a trailing instrumentation wire and were, therefore, depth limited unless lowered to near the seafloor before being released. Scott's system necessitated lowering the device to the seafloor and recovering it. These methods were not expedient for the intended use. The method selected to measure the penetrometer motions was an application of the Doppler principle (Thompson, 1977). In this method a constant frequency sound source mounted on the penetrometer is monitored at the support vessel with a hydrophone-receiver. The motion of the penetrometer relative to the hydrophone-receiver causes an apparent shift in the emitted acoustic signal (the Doppler principle). That shift is proportional to the velocity of the penetrometer. The velocity data can be analyzed to determine penetration depth and soil strength.

An experimental Doppler penetrometer was designed and built, and 10 units were tested (Beard, 1977). The results of these initial tests were encouraging. The testing showed that the acoustic output of the sound source was more than adequate to attain the maximum operational water depth, that soil penetration was satisfactory, and that a reasonable estimate of the strength profile over the depth of penetration could be calculated from the Doppler data.

Principle of Operation

The Doppler principle is stated as:

$$f' = f\left(\frac{v_f}{v_f + v}\right) \tag{1}$$

where: f' = frequency received

f = frequency transmitted

v_f = sound velocity of the immersion fluid

v = velocity of sound source (penetrometer)

The motion of the sound source, or penetrometer, relative to the receiver of the sound causes a different frequency signal to be received than was transmitted. The received frequency is a function of the transmitted frequency, the sound velocity of the immersion fluid at the source, and the velocity of the source. Since the velocity of the source is desired, Equation 1 is rewritten as:

$$v = v_f \left(\frac{f - f'}{f'} \right) \qquad (2)$$

The velocity, v, during the actual penetration event is then analyzed to determine penetration depth and soil strength.

Theory of Soil Strength Determination

Soil failure around an advancing penetrator is complex and difficult to analyze. Frontal bearing resistance, side resistance, buoyancy, inertial or drag forces, and added mass need to be considered. True (1975) has presented a soil penetration model based on Newton's second law that can be used to determine soil strength from known penetrator motion. True's model is:

$$M' \, v \frac{dv}{dz} = F_D + W_b - F_{BE} - F_{AD} - F_H \qquad (3)$$

where: M' = penetrator effective mass

v = penetrator velocity

z = soil depth

d = differential operator

F_D = external driving force

W_b = buoyant weight of penetrator

F_{BE} = bearing component force

F_{AD} = side adhesion force

F_H = inertial or drag force

The effective mass of the penetrator is equal to the mass of the penetrator plus the added mass of fluid and soil that is decelerated with the penetrator. Wendel (1950) shows that the added mass of slender, cylindrical bodies (like a soil penetrator) moving along their long axis is negligible; therefore, M' is the mass of just the penetrator.

For the Doppler penetrometer there is no external driving force because it free-falls; therefore, F_D is zero.

Terms involving soil strength are F_{BE} and F_{AD} that True formulated as:

$$F_{BE} = S_e (s_u N_c A_f) \qquad (4)$$

where: $S_{\dot{e}}$ = soil strength strain rate factor
s_u = soil undrained shear strength
N_c = bearing capacity factor
A_f = penetrator frontal area

and

$$F_{AD} = S_{\dot{e}} \left(\frac{s_u A_s \delta}{S_t} \right) \qquad (5)$$

where: A_s = penetrator side area
S_t = soil sensitivity
δ = side adhesion factor

These equations follow basic geotechnical concepts for static cases with a strain rate factor and a side adhesion factor included. It is an accepted concept that soil strength is strain rate dependent. However, there is neither a generally accepted maximum strain rate factor nor a formula to describe factor variation as a function of soil type, strain rate, and failure mechanism. True recommended a maximum strain rate factor of 4 while Prevost (1976, p. 1252) suggested a maximum of 1.5. Beard (1977), in analyzing Doppler penetrometer data, found the best fit maximum strain rate factor to be 2. True has developed a formulation that varies the strain rate factor according to penetrator velocity and diameter and undrained shear strength. The formula is:

$$S_{\dot{e}} = \frac{S_{\dot{e}}^{*}}{1 + \dfrac{1}{\sqrt{\dfrac{C_{\dot{e}}\, v}{s_u\, t} + 0.6}}} \qquad (6)$$

where: $S_{\dot{e}}^{*}$ = empirical maximum strain rate factor, 2
$C_{\dot{e}}$ = empirical strain rate coefficient, 1900 Pa-sec (40 lb-sec/ft²)
t = penetrator thickness (or diameter)

True included a side adhesion factor, δ, in Equation 5 to account for reduced side resistance from separation of the penetrator and the soil or for reduced contact pressure between the penetrator side and the soil. The side adhesion term was formulated so that it varied according to distance from the nose of the penetrator and penetrator thickness and length. Beard (1977) found this term caused fluctuations in shear strength profiles derived from penetrometer data; therefore, it is not used here in calculating F_{AD}.

The inertial force is calculated from the standard "fluid drag" equation:

$$F_H = \frac{1}{2} \rho \, C_D \, A_f \, v^2 \qquad (7)$$

where ρ is the fluid or soil mass density and C_D is the drag coefficient.

True's (1976) research showed that within the framework of his penetration model assuming the drag coefficient during soil penetration to be the same as in water was a good approximation. This assumption was made in previous work on the Doppler penetrometer (Beard, 1977) and satisfactory results were obtained. The value of C_D can be calculated using Equation 7 and the terminal velocity and frontal area of the penetrometer, the water mass density, and setting F_H equal to the buoyant weight of the penetrometer.

Substituting Equations 4, 5, 6, and 7 into Equation 3 gives

$$M_v \frac{dv}{dz} = W_b - \frac{S_e^{\bullet *}}{1 + \dfrac{1}{\sqrt{\dfrac{C_e^{\bullet} \, v}{s_u \, t} + 0.6}}} (s_u \, N_c \, A_f)$$

$$- \frac{S_e^{\bullet *}}{1 + \dfrac{1}{\sqrt{\dfrac{C_e^{\bullet} \, v}{s_u \, t} + 0.6}}} \left(\frac{s_u \, A_f}{S_t}\right) - \frac{1}{2} \rho \, C_D \, A_f \, v^2 \qquad (8)$$

Doppler penetrometer data, being velocity-time information, are not directly interpretable with Equation 8. First, the velocity-time data must be integrated to obtain depth-time data, and then these two data sets must be cross-plotted to achieve velocity-depth data. To make a detailed interpretation it is necessary to consider the soil as a series of layers and the penetrometer as a series of connected segments with the thickness of the soil layers equal to the length of the penetrometer segments. The soil strength at successive depth increments is computed from the resistance encountered by the leading segment of the penetrometer. This part of the overall penetrometer resistance is the difference between the total penetration resistance and the penetration resistance of the other segments of the penetrometer calculated for previously evaluated properties of the overlying soil layers, the inertial force, and the buoyant weight of the penetrometer. Within this computational framework Equation 8 is solved with an incremental forward difference procedure over the depth of penetration. In incremental form at depth z_i and velocity v_i Equation 8 becomes:

$$M\left[\frac{v_i - v_{i-1}}{2}\right]\left[\frac{v_i - v_{i-1}}{z_i - z_{i-1}}\right] = W - \frac{1}{N} A_f L \sum_{k=i-N+1}^{k=i} \gamma_k$$

$$- \frac{S_e^{\bullet *}}{1 + \dfrac{1}{\sqrt{\dfrac{C_e^{\bullet}(v_i + v_{i-1})}{2 s_{u(i)} t} + 0.6}}}\left[s_{u(i)} N_c A_f\right]$$

$$- \sum_{k=i-N+1}^{k=i}\left[\frac{S_e^{\bullet *}}{1 + \dfrac{1}{\sqrt{\dfrac{C_e^{\bullet}(v_i + v_{i-1})}{2 s_{u(k)} t} + 0.6}}}\right]\left[\frac{s_{u(k)} A_{f(k+i+N)}}{S_{t(k)}}\right]$$

$$- \frac{1}{2} C_D A_f \left[\frac{v_i + v_{i-1}}{2}\right]^2 \frac{1}{N} \sum_{i=i-N+1}^{i=i} \rho_i \qquad (9)$$

where: i = subscript to indicate the ith increment of depth

k = subscript to indicate the kth increment of depth

N = total number of penetrometer segments

γ = soil bulk wet density

ρ = mass density of soil and water surrounding the penetrometer

Equation 9 is solved by trial and error for the undrained shear strength at the ith depth increment. The analysis has been computerized and is documented in Beard (1983).

PURPOSE AND APPROACH

The purpose of the work being reported was twofold. First, it was desired to redesign the penetrometer to achieve a smaller, easier to handle unit and to improve the features of the sound source. Second, a validation of the penetrometer's performance in a variety of deep ocean sediments, complete with data comparison to conventionally acquired strength profiles, was needed.

The philosophy of the redesign was to maintain the design penetration depth of 9 meters (30 feet) in soft seafloors, yet reduce the penetrometer's weight, and at the same time to maintain the ability to operate in 6,000 meters (20,000 feet) of water even though the acoustic output of the sound source is reduced. Prototype testing had shown that both penetration and acoustic output were more than adequate. Another desired change was the addition of a timer to turn off the sound source a few minutes after penetration. In tests of the prototype unit, it was not uncommon for a signal to be detectable for more than an hour, thus preventing performance of another test. A combination of laboratory and at-sea tests were planned to evaluate these changes. Thirty-nine tests were performed at water depths from 30 to 5,490 meters (100 to 18,000 feet). However, the new, lower output sound source was tested to only 4,980 meters (16,090 feet). Tests were done in pelagic clays, calcareous oozes, and a variety of terrigenous-derived sediments. Test locations included sites in the Atlantic and Pacific Oceans and the Caribbean Sea. Strength data for comparison to the strength profiles derived from the penetrometer tests were usually acquired by mini-vane and triaxial shear testing of core samples.

DESIGN CHANGES

Design changes were made to both the heavy vehicles and the sound source of the penetrometer. A parametric study of penetration of shortened and therefore lighter, penetrometers into a variety of soils was made by applying penetration theory. The results showed that the vehicle could be shortened by about 0.5 meter (1.5 feet), thereby reducing the weight by 312 N (70 lb) but still able to penetrate 9 meters (30 feet) into soft seafloors.

The reduction in acoustic output was based on theoretical calculations on sound transmissions in sediment and seawater and excess signal levels measured during prototype testing. The results of the analyses indicated that the acoustic output could be reduced to 80·5 db above 0.1 Pa (1μbar) at 1 meter (3.28 feet). A power-off circuit was added to turn the sound source off about 11 minutes after power-on. This is about double the time needed to deploy and allow the penetrometer to reach the seafloor at the maximum operating water depth. A re-initiation feature was included in the timer so that the timer could be reset if the sound source was removed from the water and wiped dry. With this feature, if the penetrometer was immersed but its release was delayed and it was thought that the timer might run down, the penetrometer could be lifted out of the water to re-start the timer.

DESCRIPTION OF EQUIPMENT

The Doppler penetrometer system has three components: (1) a penetrometer complete with a sound source mounted on it, (2) a hydrophone complete with preamplifier, and (3) a receiver for processing the incoming data (Figure 1).

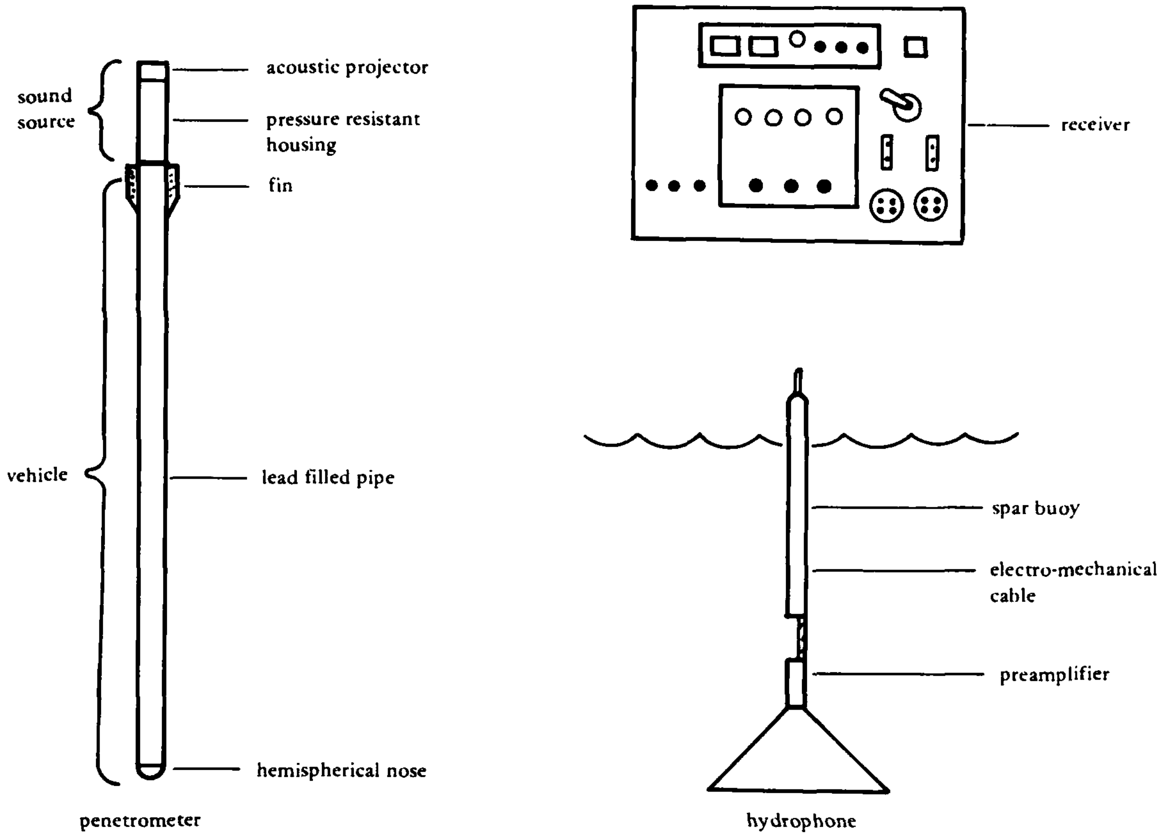

Figure 1. Expendable Doppler penetrometer components.

Penetrometer

The penetrometer (Figure 2) has two parts: (1) a heavy hydrodynamically shaped vehicle for speeding the penetrometer to the seafloor and for providing the impetus for penetrating the seafloor and (2) an accurately controlled sound source that transmits signals which are monitored by the hydrophone at the ship to determine penetrometer velocity.

The vehicle is a lead-filled 2-meter- (6.5-foot-) long, 90-mm- (3-1/2-inch-) diameter pipe. A steel hemisphere is welded to the nose of the vehicle. The upper end is capped with a circular steel plate with a centered stud for attaching the sound source. Three equally spaced fins at the upper end provide stability for the falling penetrometer. The vehicle weighs about 1.31 kN (295 pounds).

The redesigned sound source (Figure 3) consists of a projector, power supply, electronic circuitry, and a protective pressure-resistant housing. It weighs about 89 N (20 pounds) and is 0.3 meter (1 foot) long and 90 mm (3-1/2 inches) in diameter. The sound source screws onto the stud provided at the upper end of the penetrometer vehicle. The

acoustic output of the sound source is a minimum of 80 5 db above 0.1 Pa (1μbar) at 1 meter (3.28 feet). The frequency is 12,000 ±1 Hertz. It starts transmitting when immersed in seawater, and is turned off by a timer after about 11 minutes of operation. When the sound source is removed from seawater, it stops transmitting and the timer automatically resets to zero.

When assembled, the penetrometer is a 1.40-kN (315-pound), 2.3-meter- (7.5-foot-) long, 90-mm- (3-1/2-inch-) diameter package (see Figure 3). The penetrometer attains a free-fall terminal velocity of 25 to 27 m/sec (82 to 88 fps) and penetrates about 9 meters (30 feet) into soft clay seafloors.

Hydrophone

The hydrophone used to pick up the signal from the penetrometer can be lowered 30 meters (100 feet) below the sea surface to reduce ship, wave, and other surface-generated noise. Usually it is suspended from a spar buoy to minimize vertical motion. Vertical motion of the hydrophone creates a Doppler shift in the signal which could be classified as noise in the Doppler data from a penetrometer. It has a plug-in bandpass preamplifier and an overall sensitivity of -65 db referenced to 1V/0.1 Pa (1μbar) of pressure. Other features include a 0.33-radian (19-degree) beam pattern at 12,000 Hertz and a front-to-back ratio of 20 db. Absolute level calibration facilities are also provided.

Receiver

A receiver (Figure 4) is used to process the Doppler-shifted penetrometer data signal that is picked up with the hydrophone. The hard-limiting receiver electronics consists of various bandpass filters and calibration crystals, a frequency converter, and a frequency discriminator. A self-contained, sealed, lead acid battery pack or line power can be used to operate the receiver. Numerous outputs are provided on the receiver, including the "raw" frequency signal and a voltage analog of the penetrometer's velocity. Time output is also provided as a 1-msec tick and a unique tick every 10 msec. The receiver components are housed in a splash-proof aluminum case with appropriate control switches and plug-in jacks.

The high-gain hard limiter takes the incoming signal and amplifies it to saturation levels, thereby maximizing the low-end signal level that can be processed. The frequency converter then shifts the 12,000-Hertz signal down to a standard instrumentation frequency of about 3,900 Hertz. This magnifies the Doppler shift as a percentage of the total frequency. Next, the signal is processed by a frequency-modulated discriminator into a direct current voltage. The amplitude of the direct current voltage is the analog of the Doppler-shifted signal and is readily plotted or recorded.

Figure 2. Penetrometer sound source showing electronics and battery.

Figure 3. Expendable Doppler ready for deployment

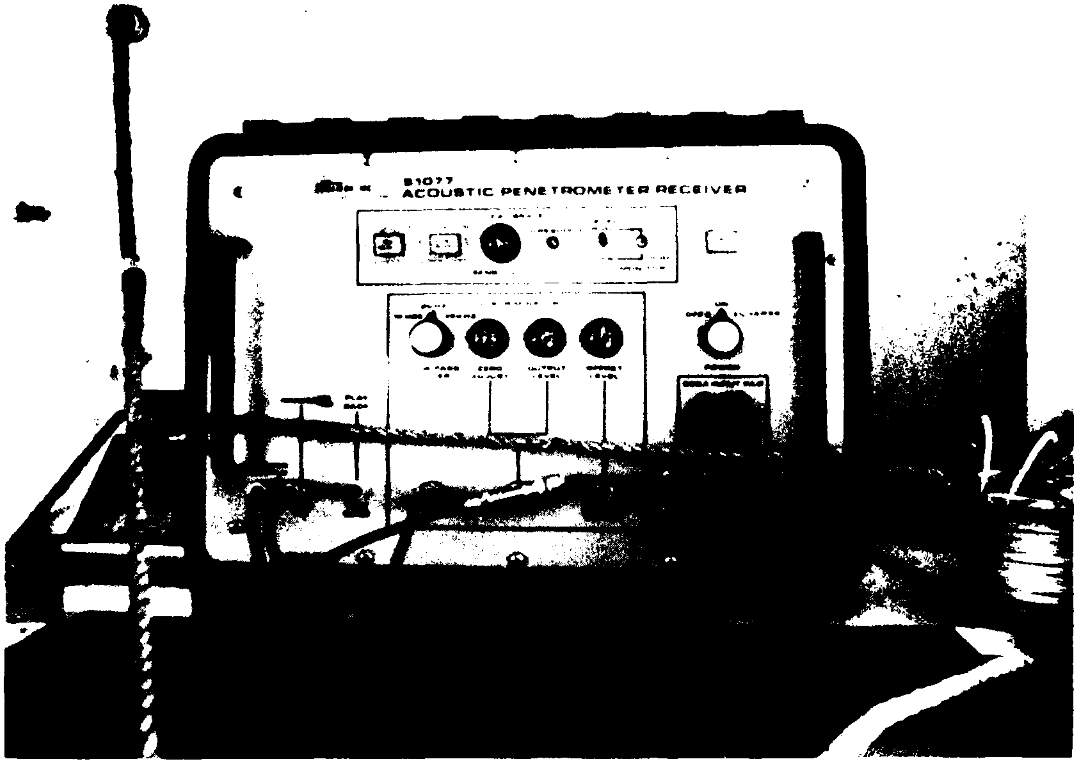

Figure 4. Penetrometer receiver.

TEST PROGRAM AND PROCEDURES

Beard (1977) reported 11 Doppler penetrometer tests off the southern California coast in soils described as silty clays and clayey silts. Those tests demonstrated that: (1) the penetrometer would achieve more than the design penetration of 9 meters (30 feet) in soft clay, (2) the concept of a Doppler data system was workable and reliable, (3) the data could be reduced to provide an estimate of a soil's shear strength profile, and (4) the acoustic output was more than enough to achieve operation at a water depth of 6,000 meters (20,000 feet).

To evaluate the design changes, a program was begun consisting of tests in soft seafloors and at great water depths using penetrometers of the new and the prototype designs. In addition, measurements of the acoustic output of the redesigned penetrometer were made at the TRANSDECK facility of the Naval Ocean Systems Center, San Diego. To evaluate the penetrometer's performance and the ability to reduce the data to strength profiles in a variety of seafloors, tests were performed in pelagic clay, calcareous ooze, and a variety of terrigenous deposits ranging from sandy soils to silty clays. A summary of all the site locations, water depths, and soils is given in Table 1, including data for sites I through IV that were reported previously (Beard, 1977).

Table 1. Site Descriptions

Date	Site No.	General Location	Geographic Coordinates		Water Depth		Soil Description
			Latitude (N)	Longitude (W)	Meters	Feet	
Aug 1976	I	Santa Barbara Channel	34°17.2'	119°42.8'	180	600	Nonuniform terrigenous deposit. Firm sandy clayey silt to 1 m; clayey silt below 1 m (ML-MH).
Aug 1976	II	Santa Barbara Channel	34°16.5'	119°	370	1,200	Soft, uniform terrigenous plastic clayey silt (MH).
Aug 1976	III	Santa Cruz Basin	33°51'	119°41'	1,830	6,000	Soft, terrigenous silty clay with occasional sand lens. (MH).
Aug 1976	IV	Santa Monica Basin	33°43.5'	119°05'	880	2,890	Uncored terrigenous soil. Thought to be cohesive based on soil found on anchor fluke.
Dec 1976	V	N.E. Pacific Ocean	21°32.6'	143°38.6'	5,430	17,800	Pelagic clay.
Dec 1976	VI	San Diego Trough	32°33.5'	117°29'	1,230	4,040	Firm, terrigenous clayey silt (MH); some sand lenses.
Sep 1977	VII	Blake Plateau	27°59.8'	77°10.8'	1,130	3,700	Calcareous ooze, cohesionless. Coarse grained, very sensitive, 80% carbonate content.
Sep 1977	VIII	Nares Abyssal Plain	21°01'	66°24'	5,490	18,000	Pelagic clay, soft manganese nodules.
Jun 1978	IX	Sohm Abyssal Plain	34°43'	61°24'	4,570	14,990	Pelagic clay, soft.
Aug 1978	X	Santa Cruz Basin	33°51'	119°41'	1,700	5,580	Terrigenous silty clay with occasional sand lenses.
Oct 1978	XI	Gulf Stream Outer Ridge	34°49.9'	65°50.5'	4,770	15,650	Pelagic clay.
Oct 1978	XII	Gulf Stream Outer Ridge	36°04.7'	66°13.4'	4,835	15,860	Pelagic clay.
Oct 1978	XIII	Gulf Stream Outer Ridge	36°09.8'	66°17.2'	4,908	16,090	Pelagic clay.
Dec 1978	XIV	San Pedro Bay	33°35'	118°07.7'	75	250	Terrigenous sandy silt (ML) to clayey silt to 4.5 m, silty clay below.

continued

Table 1. Continued

Date	Site No.	General Location	Geographic Coordinates		Water Depth		Soil Description
			Latitude (N)	Longitude (W)	Meters	Feet	
Dec 1978	XV	San Pedro Bay	33°34.4'	118°07.2'	165	540	Terrigenous soft to medium silt (CL) to 6 m, stiff clayey silt below 6 m.
Dec 1978	XVI	San Pedro Bay	33°33.9'	118°07'	215	700	Terrigenous very soft to medium stiff clayey silt (ML-CL).
Feb 1979	XVII	Santa Barbara Channel	34°11'	119°27.8'	95	310	Terrigenous soft to firm silty clay (CL) to 3 m, medium dense sands and silts 3 to 6 m.
Feb 1979	XVIII	Santa Barbara Channel	34°19.9'	119°33.4'	55	180	Terrigenous sandy silt (ML), hard, low plasticity.
Jun 1979	XIX	Puget Sound	48°03'	122°46'	30	100	Soft silty *organic clay (OH)* of medium to high plasticity.
Oct 1979	XX	Caribbean Sea	16°58.9'	74°01.2'	3,730	12,230	Calcareous ooze, 50% carbonate carbon, 60% clay sized, sensitive, firm.
Oct 1979	XXI	Caribbean Sea	17°0.9'	79°30.5'	1,130	3,710	Calcareous ooze, 74% carbonate carbon, 60% clay sized, very sensitive, soft.
Oct 1979	XXII	Caribbean Sea	15°34.9'	78°22.8'	700	2,300	Calcareous ooze, 60% carbonate carbon, 55% clay sized, moderately sensitive, soft.
Oct 1979	XXIII	Caribbean Sea	14°46.4'	78°3.7'	1,880	6,170	Calcareous ooze, 51% carbonate carbon, 35% clay sized, very soft.
Oct 1979	XXIV	Caribbean Sea	13°16.2'	78°2.6'	3,690	12,000	Calcareous ooze, 44% carbonate carbon, sandy clay, very soft.

The test procedure was similar for each test. Prior to arriving on-station, a penetrometer was assembled and checked out. Once on-station, the ship's propellers were disengaged and the hydrophone placed in the water suspended on an elastic cord below a spar buoy. The instrumentation was calibrated at frequencies representing 0 and 15.2 m/sec (50 fps). A penetrometer was placed over the side of the ship and wetted to test-start it. On indication that the signal was being received, recorders were started and the penetrometer released. Typically the raw frequency signal, the converter frequency signal, the Doppler shift analog, and the time pulse were recorded on magnetic tape. Much of these data were back-up to the Doppler shift analog. The analog data and time pulse were also recorded on paper.

Cores were taken at each site to provide conventional acquired strength data for comparison to strength to be derived from the penetrometer data. In some cases, historical core data were available and new cores were not taken. The strength of the cored sediments was determined by either of two methods, depending on the nature of the sample.

Mini-vane shear tests were performed on the cohesive soils. Because coring disturbs the sediment, the strengths measured on cores are usually somewhat lower than in-situ values. To minimize disturbance, the cores were handled carefully, stored under refrigeration, isolated from vibrations, and tested as soon as possible (often immediately after coring). Mini-vane strength data can be corrected for disturbance using a procedure given by Lee (1973a). However, corrections were not made to any of the vane data reported for two reasons. In some cases, the data were historical and the corrections could not be made. For the other cohesive sediments, corrections were not warranted because the sediments were of medium to high plasticity (Lee, 1979). For sediments of low plasticity that were easily disturbed, mini-vane shear tests are inappropriate. For these soils, strength profiles were developed from triaxial shear data.

The concept of developing a strength profile for disturbed soils was discussed by Lee (1973b) and was followed in developing strength profiles in this report except that a critical-state model was used to calculate strengths (Mayne, 1980). In this procedure, the triaxial test samples are consolidated to stresses much above in-situ values to remove the effects of disturbance. The triaxial test data from these normally consolidated samples are used to determine the critical-state soil constants. These constants are necessary for calculating strengths at other stress states. The stress state parameters needed to calculate a profile are the overburden pressure and the OCR (overconsolidation ratio). The overburden pressure is derived from density measurements. The OCR is determined as a function of overburden pressure by applying the critical-state model to triaxial test data from several overconsolidated samples. With this information, the strength profile is computed. This type of procedure is the only way to reliably estimate the strength profile of sediments that are not suitable for direct strength measurements.

DATA PROCESSING

All of the data were reduced following the general procedures given in the Theory of Soil Strength Determination section of this document and the specific recommendations and procedures given below.

The velocity versus time analogs of the Doppler-shifted signal were reduced to obtain sediment strength. To be analyzed, these data were digitized, calibrated, and processed with a microcomputer. After digitizing, the data were processed with two computer programs. First, a program was used to calibrate, filter, and edit the data down to the penetration event. The filtering routine included random spike rejection, an averaging filter of selectable bandwidth, and straight lining across signal dropouts. Not all of these features were used on a given data set. The second program was used to correct the velocity data, fit a cubic-spline curve through the data, calculate velocity and deceleration profiles and, finally, to calculate the undrained shear strength profile.

One difficulty in editing the data down to the penetration event was selecting the impact point, which is the point where the velocity data first curves away from the straight line representing terminal velocity prior to impact. For stiff soils or when the data trace was very clean, this difficulty was minor. For soft soils or when the data trace was noisy, perhaps the upper 1 meter (3 feet) of penetration was missed. After 1 meter (3 feet) of penetration, even in soft soils, the velocity change was quite apparent. The difficulty here was largely due to instrumentation noise and, to a lesser degree, the nature of the Doppler penetrometer. To ease this difficulty, a reference line was placed through the terminal velocity so that the impact point was easier to find.

For these tests, the velocity analog of the Doppler-shifted data output by the receiver was scaled with a calibration for sound velocity in water and in the sediment of 1,463 m/sec (4,800 fps); but sound velocity varied with temperature, pressure, and sediment type. Therefore, a better conversion to penetrometer velocity was made by estimating or measuring the true sound velocity. The estimates of the sound velocity in water were made from Figure 5. The conversion, however, was complicated by the fact that the sound velocity in sediment differs from that of the near-bottom water; hence, when the sound source was buried in the sediment, additional assumptions were made about sound velocity.

Much sediment sound velocity data were summarized by Hamilton and Bachman (1982). It was noted that the sound velocities of ocean sediments varied by sediment type; were, at the sediment surface, proportional to the sound velocity of the near-bottom water; and increased linearly with depth. Sound velocities were also compared to expected Doppler penetrometer penetration in the sediments. In general, as sound velocity increased, penetration decreased. Therefore, the program was set up to select sediment sound velocity as a function of total penetration and the previously determined water sound velocity. The sediment sound velocity was assumed to be 1.5% less than the bottom water when penetration exceeds 7.5 meters (25 feet), to be equal to that of the bottom water when penetration was between 4.5 and 7.5 meters (15 and 25 feet), and was assumed to be 5% greater than the bottom water when

penetration was less than 4.5 meters (15 feet). The sound velocity was also increased at 0.5 m/sec/m (0.5 fps/ft) of sediment depth. It was further assumed that the sound velocity transitioned from that of the bottom water to that of the sediment over the upper 1 meter (3 feet) of the sediment because of a physical water-soil mixing process at the base of the penetrator. With this more accurate sound velocity profile for the water and the sediment, the velocity data were refigured using Equation 2.

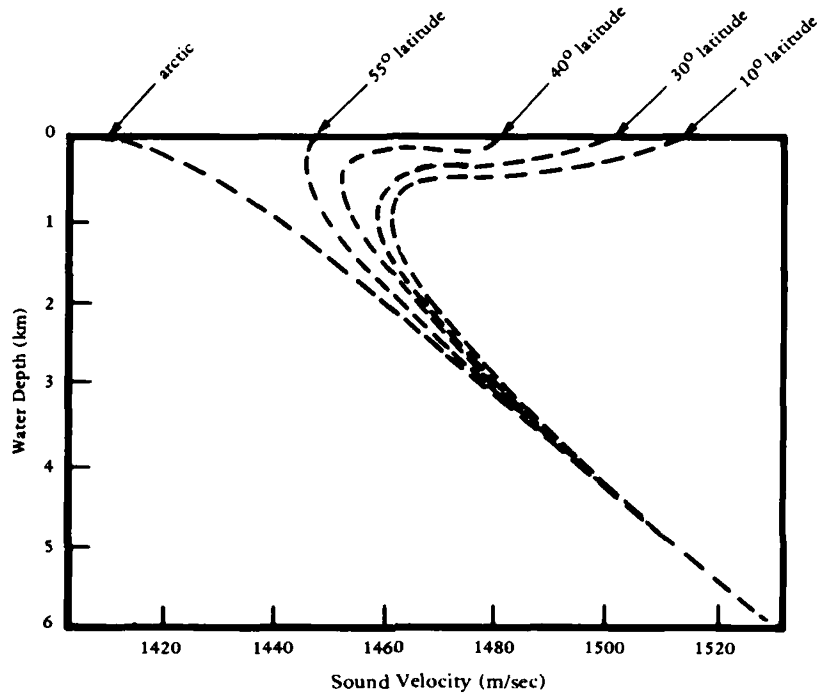

Figure 5. Sound velocity in seawater as a function of water depth and latitude (after Myers et al., p. 3-7).

Additional smoothing of the data during the penetration phase was done with a cubic-spline curve fitting routine. The intensity of the smoothing was varied to accommodate the roughness of the data. Care was taken not to change the shape of the velocity-time curve, only to remove roughness.

The velocity-depth profile data set was used to calculate the soil strength profile. It was determined by integrating the velocity-time curve to get a depth-time curve and then cross-plotting these two data sets.

The deceleration-depth profile was determined by differentiating the velocity-time data to get deceleration-time data and cross-plotting this data with the depth-time data. The deceleration profile was used only to indicate the shape of the strength profile curve.

Shear strength was calculated with an incremental depth algorithm (Equation 9). To solve the algorithm, assumptions were made about the sediment's bulk wet density and sensitivity. The bulk wet density was used in calculating buoyancy forces on the penetrator. The bulk wet

density was set at 1,440 kg/m³ (90 pcf) when penetration exceeded 7.5 meters (25 feet), 1,600 kg/m³ (100 pcf) for penetration between 4.5 and 8 meters (15 to 25 feet), and 1,760 kg/m³ (110 pcf) when penetration was is less than 4.5 meters (15 feet). Parametric studies showed that these assumptions held errors to less than 1%.

The sensitivity assumption played a more important role in the shear strength profile. The sensitivities assumed in reducing the data in this report are given in Table 2. These values are based on NCEL's experiences in testing seafloor soils as reported by Lee and Clausner (1979).

Table 2. Assumed Sediment Sensitivities

Sediment	Sensitivity
Pelagic Clay	3
Calcareous Ooze	4-6
Terrigenous Clay	3
Clayey Silt	2
Silty Sand/Sandy Silt	2

For calcareous oozes a value of 4 was used if the particle size was expected to be in the clay or silt range and a value of 6 for an ooze composed of hollow tests. A study of the errors in strengths calculated with an incorrect sensitivity was made. It was found that calculated shear strength is more sensitive in sediments of low sensitivity. For example, if a soil has a sensitivity of 3, but a value of 2 is assumed, the sediment strength will be estimated about 30% low. However, if the soil has a sensitivity of 5, but a value of 4 is assumed, the sediment strength will be estimated about 15% low. For this same sediment, if a value of 6 is assumed, the estimated strength will be about 15% high.

Another assumption in the data reduction was that the drag coefficient in the inertial term was the same in soil as it was in water. For the Doppler penetrometer, the inertial term played a relatively small role in decelerating the penetrometer; i.e., the force terms involving soil strength are much larger. Hence, the assumption about the drag coefficient was not significant as a source of error in the data reduction.

TEST RESULTS

The acoustic output of the redesigned sound sources measured at the TRANSDECK facility was 80 db above 1μbar at 1 meter, theoretically sufficient for operation in 6,000 meters (20,000 feet) of water. A test

was successfully performed at a water depth of about 5,000 meters (16,000 feet) with the new sound source. No deeper test was conducted with the redesigned sound source. The timer circuit worked as designed.

The penetration data were reduced to determine penetration depths and undrained shear strength profiles. These analyses were done using procedures and computer programs described in detail by Beard (1983) and briefly covered in the preceding section. These data are compared graphically to undrained shear strength profiles from the cores. The profiles from the cores were determined as described under TEST PROGRAM AND PROCEDURES.

The site write-ups that follow briefly describe the quality of the penetrometer data recorded at sea and state the soil sensitivities used to reduce the data, which were in accordance with the recommendations of Table 2. The type of core and other pertinent sampling, and sediment testing procedures are also presented. The graphical comparisons of the penetrometer and comparative undrained shear strength profiles are qualitatively discussed. The results from sites I through IV were presented by Beard (1977) and are not reproduced here.

Operationally, few problems have been encountered in deploying penetrometers. Once, a line got fouled on the penetrometer and was pulled to the seafloor. Once, when tests were conducted from a very unstable platform in rough weather, two penetrometers were literally thrown off the deck. Judging from the data received this would seem to be an acceptable but not a preferred procedure. Deployments were made without undue problems in sea state 4 and occasionally in sea state 5 from ships about 60 meters (200 feet) long.

Site V, N. E. Pacific Ocean

Two tests were conducted at this site 700 miles east of Hawaii at a water depth of about 5,430 meters (17,000 feet) using 1.69-kN (380-pound) penetrometers with 90-db sound sources. Both tests were successful, and good signals were recorded. A 117-mm- (4.6-inch-) diam by 3.6-meter (12-foot) core (a recovery ratio of 0.3) and a box core were taken. The soil at this site was a highly plastic pelagic brown clay. A comparison of shear strengths measured on the core by laboratory mini-vane and calculated from the penetrometer data with an assumed sensitivity of 3 is presented in Figure 6. The data compare well, although there is some question as to the depth the core sample came from. The data from the two penetrometer tests are consistent.

Site VI, San Diego Trough

One test was performed in the San Diego Trough off the Southern California coast at a water depth of 1,370 meters (4,490 feet) with a 1.69-kN (380-pound) penetrometer and a 90-db sound source. The test was successful; a good signal was received and recorded. No core was taken. Subbottom acoustic records indicated a layered seafloor with apparent reflectors at about 3.6 and 5.8 meters (12 and 19 feet). Historical geotechnical data from the area includes in-situ and laboratory mini-vanes. The data extends to only about 1.5 meters (4.9 feet) of depth and have been presented by Simpson (1974). These geotechnical data are

plotted with the reduced penetrometer data in Figure 7. The penetrometer data were reduced with an assumed sensitivity of 3. The mini-vane data offer little comparison to the penetrometer because they are so shallow. However, the moderate penetration is reflected in the strengths calculated from the penetrometer data. It is noteworthy that the two layers of soil with higher strength corresponded to the layers detected with the subbottom profiles.

Site VII, Blake Plateau

Three tests were conducted at the Blake Plateau site north of the Bahama Islands at a water depth of about 1,130 meters (3,700 feet). One was performed with a 1.69-kN (380-pound) penetrometer and two with the new 1.40-kN (315-pound) penetrometer. For each test a 90-db sound source was used. In each test a good signal was received until penetration reached 9 to 12 meters (30 to 40 feet). Then the direct signal was overpowered by a reflected signal that had been transmitted from the sound source, reflected off the ocean surface back to the seafloor, and back again to the ocean surface and the hydrophone. As a result, a full data trace was not recorded. Assuming that the soil was similar at depth, penetration was estimated to have been about 15 meters (50 feet) in each test. The comparative data at this site are from historical data from Lee (1976). Lee took a 5.5-meter- (18-foot-) long piston core 67 mm (2.6 inches) in diameter at this site and found a coarse-grained calcareous ooze. Because the sample was easily disturbed, a series of triaxial tests were conducted to develop the in-situ strength profile. The method used by Lee is similar to that described in TEST PROGRAM AND PROCEDURES except that several consolidation tests are required. The sensitivity assumed for the penetrometer data reduction was 6. This value was used because the predominant soil grains were hollow foraminifera tests that are easily crushed, thereby releasing entrained water that acts as a lubricant. A comparison of the laboratory-derived and penetrometer strength profiles is given in Figure 8. Reasonable agreement is apparent, although there is considerable scatter in the penetrometer data in the upper 5 meters (16 feet). The low strength from the penetrometer data at depth [20 kPa at 12 meters (2.9 psi at 40 feet)] is consistent with the very deep penetration achieved.

Site VIII, Nares Abyssal Plain

At the Nares Abyssal Plain north of Puerto Rico at a water depth of 5,335 meters (17,500 feet), two tests, both of which were successful, were performed. The first was done with the 1.69-kN (380-pound) penetrometer and the second with the 1.40-kN (315-pound) penetrometer. Both used 90-db sound sources. A 7.6-meter (25-foot), 67-mm- (2.6-inch-) diam piston core was taken. The soil was highly plastic pelagic clay. Comparison of laboratory mini-vane shear test results and the two penetrometer test results is shown in Figure 9. The penetrometer data were reduced with an assumed sensitivity of 3. Figure 9 shows the two penetrometer strength profiles to be in good agreement, and it appears the strength profiles are consistent with the moderate penetration achieved. The low strength profile from the laboratory mini-vane may be more an indication of disturbance than an indication of the true in-situ strength.

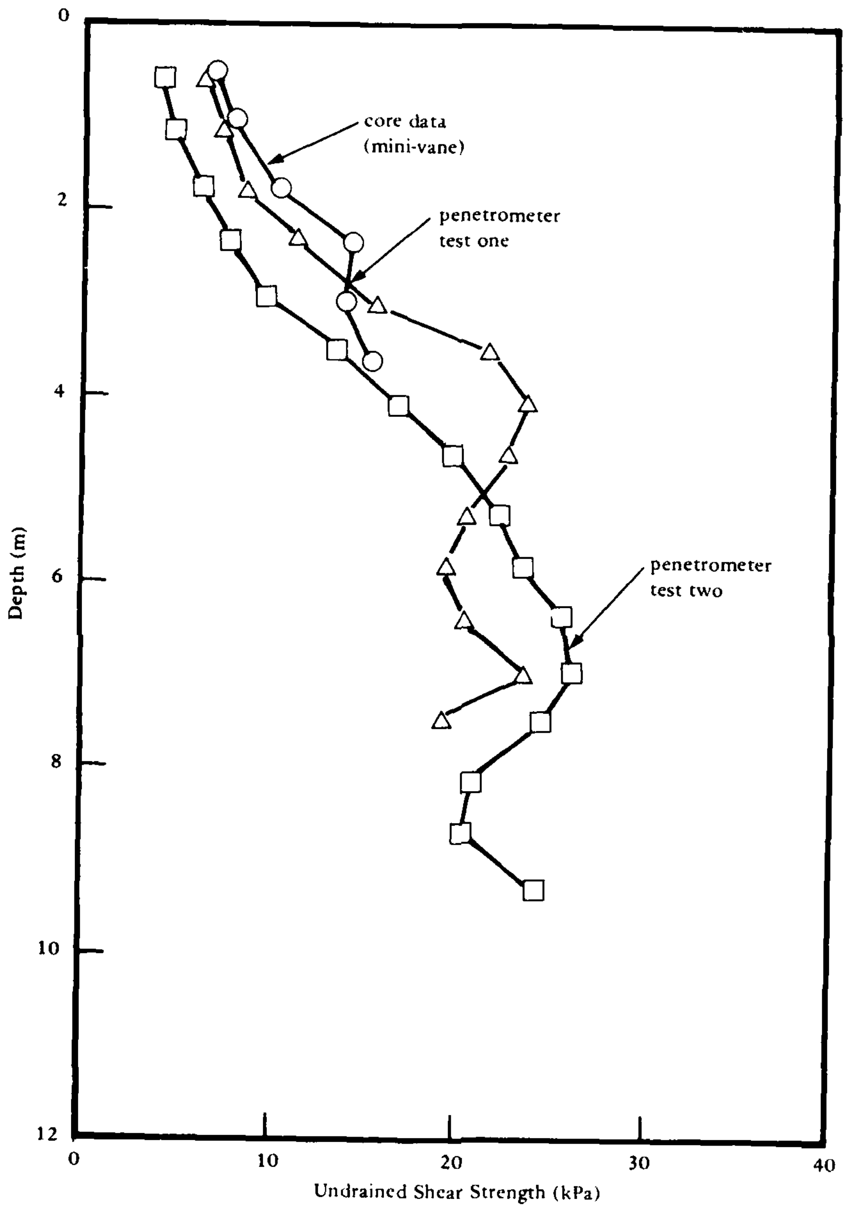

Figure 6. Comparative strength data at Site V, Northeast Pacific Ocean, pelagic clay.

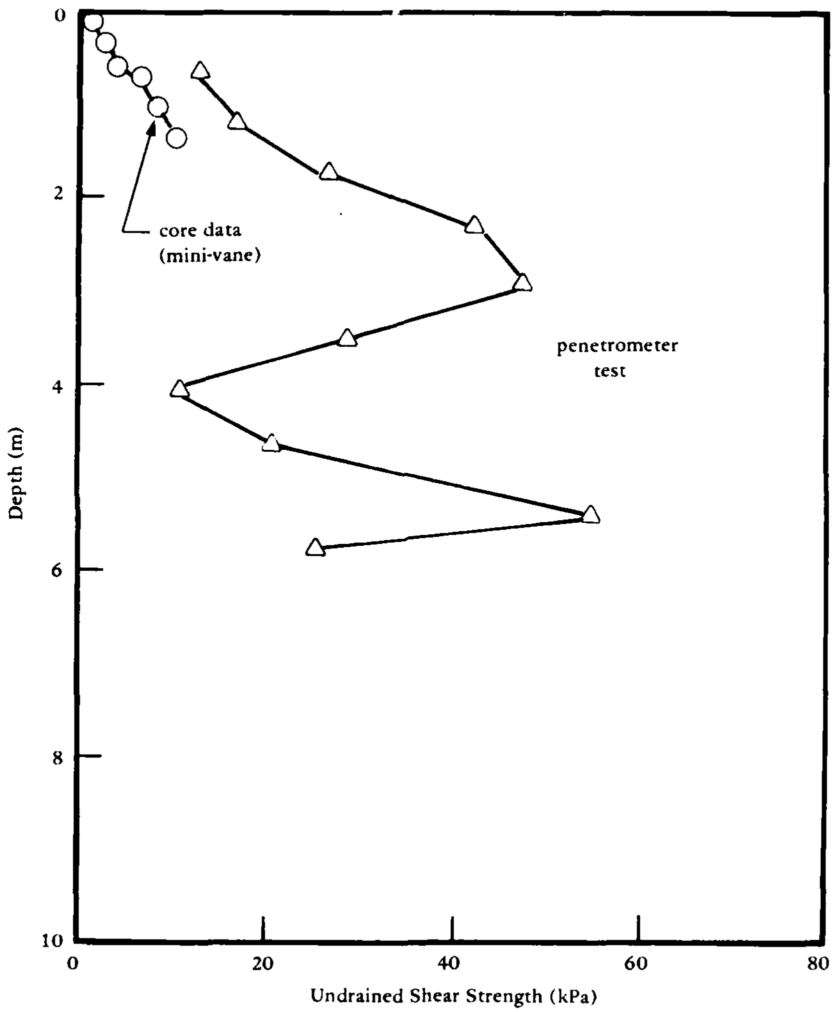

Figure 7. Comparative undrained shear strength data at Site VI, San Diego Trough, terrigenous soils.

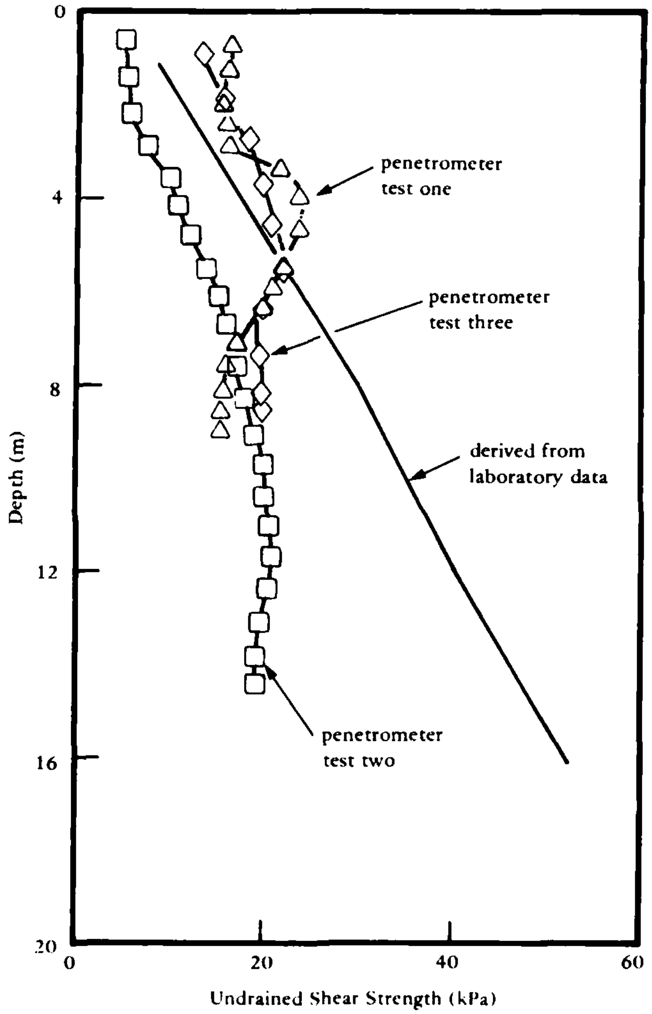

Figure 8. Comparative undrained shear strength data at Site VII, Blake Plateau, calcareous ooze.

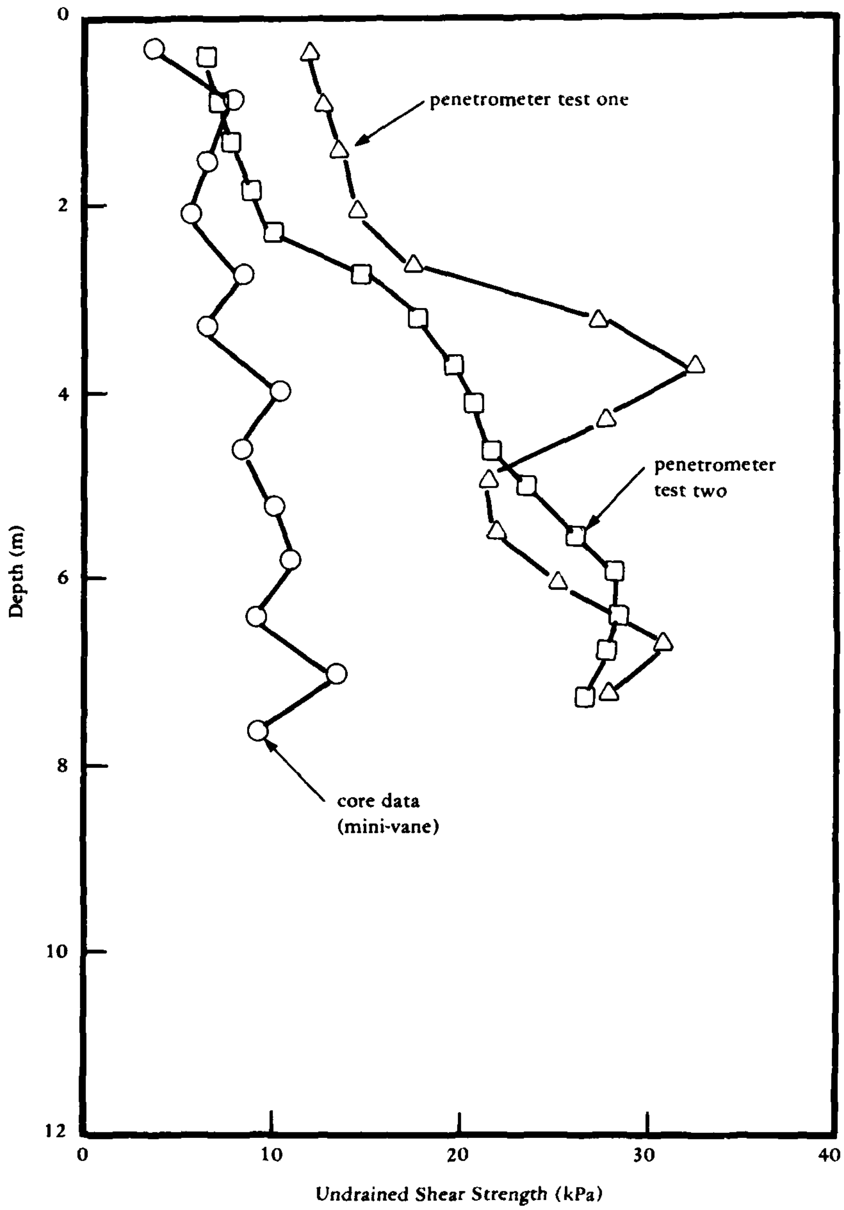

Figure 9. Comparative undrained shear strength data at Site VIII, Nares Abyssal Plain, pelagic clay.

Site IX, Sohm Abyssal Plain

Two tests were attempted at this site north of Bermuda in 4,305 meters (14,120 feet) of water. For both tests the newer 80-db sound sources and 1.40-kN (315-pound) penetrometer were used. During each test the signal was lost after about 10 seconds of operation. Pressure vessel testing and sound pressure level measurements of preproduction units had not revealed any problems. Subsequent to these two field tests a hydrodynamic study of the sound source was initiated to determine if the oil-filled rubber boot that enclosed the acoustic projector was deforming and failing at high penetrometer velocities. High velocity water tunnel tests showed this to be true; subsequently, all the sources were retrofitted with a rubber-like casting over the acoustic projector.

Site X, Santa Cruz Basin

Three tests were done at this site to verify that the repaired sound sources were working properly. The site is in about 1,830 meters (6,000 feet) of water off the Southern California coast. Navigation was lost on this cruise, and the site was located by radar ranges to prominent locations on a nearby island. The 1.40-kN (315-pound) penetrometers were used for these tests. During the first test the recorder was turned off before the penetrometer reached the seafloor. Good data were recovered on the second and third tests which were conducted considerably west of the intended site and on the slope of the basin's boundary at water depths considerably less than the 1830-meter (6,000-foot) site depth. A comparison of the penetrometer data to core data for this particular set of tests is not considered meaningful because the penetrometers were not dropped near the coring site. Therefore, a comparison graph is not presented.

Sites XI, XII, and XIII, Gulf Stream Outer Ridge

Tests performed on the Gulf Stream Outer Ridge were done at three different locations by the University of Rhode Island (Silva and Baldwin, 1979). Site XI, where two penetrometers were dropped, was in 4,770 meters (15,650 feet) of water at the top of the ridge. Site XII, where one penetrometer was dropped, was in 4,835 meters (15,860 feet) of water on the side of the ridge. Site XIII, where one penetrometer was dropped, was in 4,908 meters (16,090 feet) of water at the toe of the ridge. The 1.40-kN (315-pound) penetrometers with 80-db sound sources were used in all of these tests. A good signal was recorded for each of these tests, except for the first test at Site XI when a noisy signal was recorded. A 102-mm- (4-inch-) diam gravity core was taken at each site, extruded from the core tube, and tested aboard the ship by minivane to determine strength profiles. Soil at each site consisted of a high plasticity pelagic clay. The median diameter of the soil decreased down the ridge from 0.0017 mm at the top to 0.0007 mm at the toe. Comparisons of these data to strength profiles determined from the penetrometer tests using an assumed sensitivity of 3 are shown in Figures 10, 11, and 12.

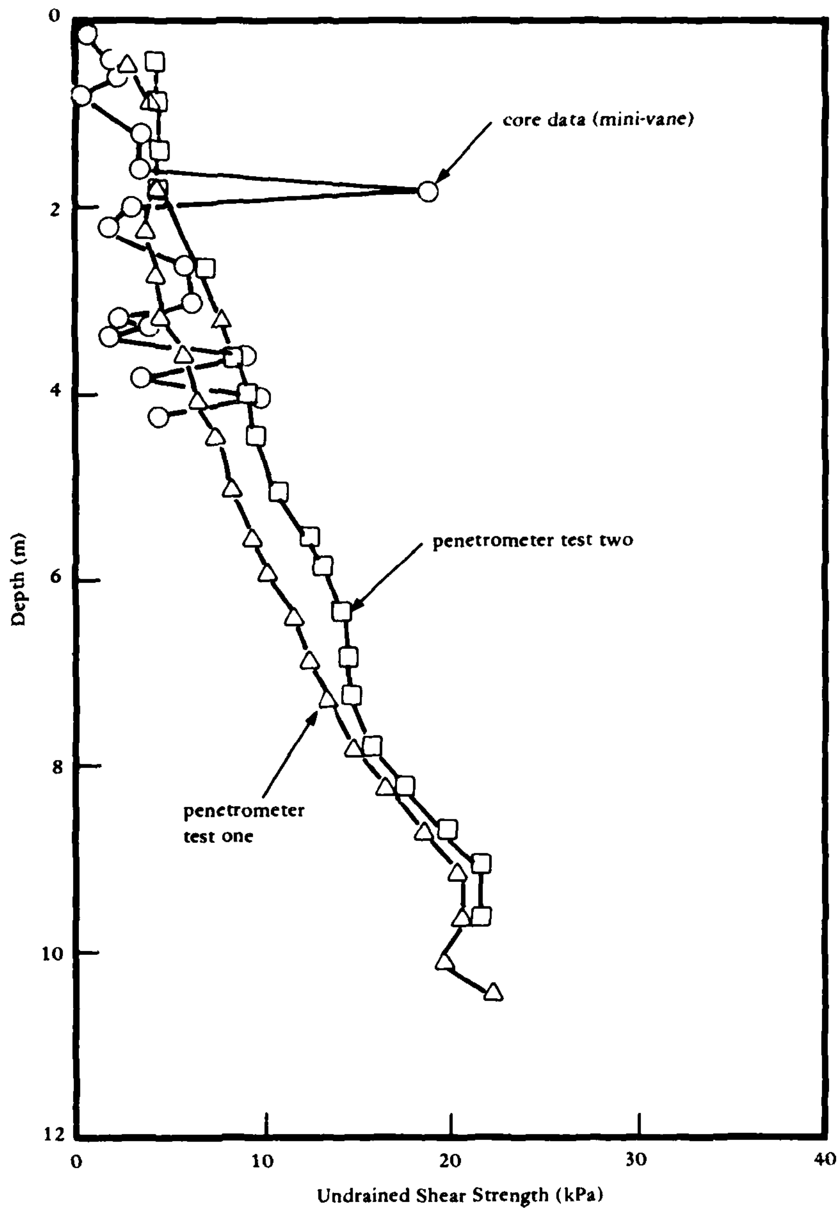

Figure 10. Comparative undrained shear strength data at Site XI, Gulf Stream Outer Ridge, pelagic clay.

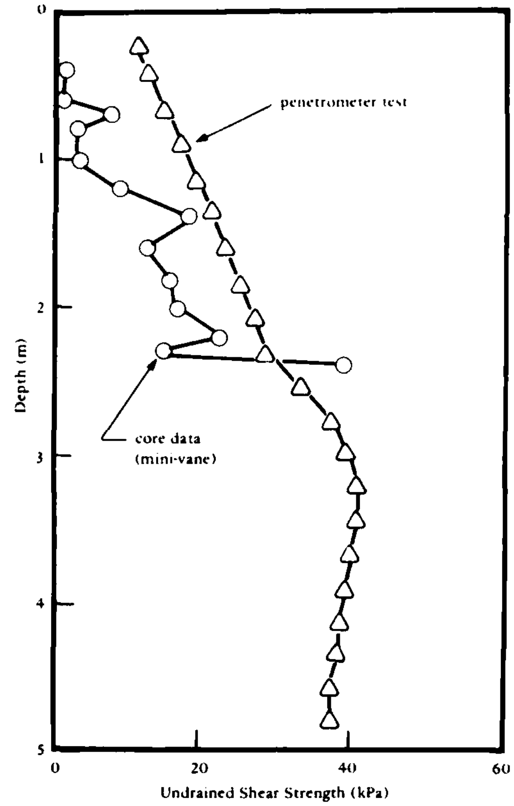

Figure 11. Comparative undrained shear strength data at Site XII, Gulf Stream Outer Ridge, pelagic clay.

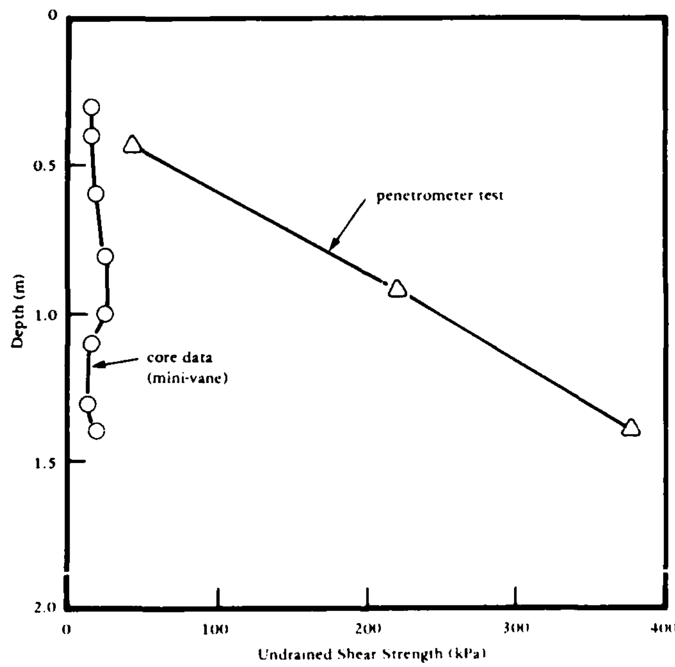

Figure 12. Comparative undrained shear strength data at Site XIII, Gulf Stream Outer Ridge, pelagic clay.

It was planned to drop two penetrometers at each site, but several penetrometers were found to be faulty (erratic frequency) prior to deployment. This problem was traced to a bad lot of transistors. Subsequently, all the remaining sound sources were repaired by removing and replacing this type of transistor.

At Site XI the strength profiles from the penetrometers are in good agreement with each other and the mini-vane strengths over the depth of the core [≅ 4 meters (13 feet)]. The penetrometer strengths seem consistent with the fairly deep penetrations achieved. At Site XII the mini-vane and penetrometer data are in fair agreement over the depth of the core. Note that considerably less penetrometer penetration was achieved than at Site XI and that higher strengths are indicated. At Site XIII there is a major unexplained difference between the core and penetrometer strength profiles. The penetrometer record was very clean and indicated very little penetration [≅ 0.5 meter (2 feet)] and, hence, a hard seafloor. The core data do not reflect this hard seafloor, but only 1.3 meters (4 feet) of core penetration was achieved. The conflicting data suggest either a seafloor of highly variable strength or that the penetrometer impacted on a turbidite.

Site XIV, San Pedro Bay

Two penetrometer tests were performed at this site in San Pedro Bay off the Southern California coast in 75 meters (250 feet) of water by Woodward-Clyde Consultants (1979a). Both tests were done with 1.40-kN (315-pound) penetrometers mounted with 80-db sound sources. Fair, but noisy, signals were recorded for each test. Soil data were acquired by a variety of different tests on samples recovered from a 76-mm- (3-inch-) OD drill string with a Shelby tube sampler. Only mini-vane and unconsolidated undrained triaxial shear data are used for comparison with the penetrometer data. These data are representative of fall cone, torvane, and pocket penetrometer results. The soil at this site was of terrigenous origin, being a slightly plastic sandy silt to clayey silt in the top 3.8 meters (12.5 feet) and low plasticity silty clay below that depth. Figure 13 presents a comparison of the penetrometer shear strength data and the mini-vane and triaxial data. The penetrometer data were reduced with an assumed sensitivity of 2. Figure 13 shows the penetrometer data to be very consistent from test to test and in good agreement with the shear strength profile from triaxial shear testing but somewhat higher than the mini-vane data. The high strengths are consistent with the shallow penetration achieved. Because the soil was of slight plasticity over the range of penetration, the triaxial data probably give a better indication of the in-situ strength than the mini-vane data. However, the core samples were probably somewhat disturbed, having been obtained by driving a tube out the end of a drill string with a hammer.

Site XV, San Pedro Bay

This site was in 165 meters (540 feet) of water off the Southern California coast. Two penetrometers were tested here by Woodward-Clyde Consultants (1979a), each of which was a 1.40-kN (315-pound) unit with

80-db sound sources attached. Good, but noisy, data were recovered from both tests. Soil strength data to compare with the penetrometer data were acquired in the same manner as for Site XIV. The soil at this site was a low plasticity clayey silt. A comparison of the penetrometer shear strength data and the mini-vane and unconsolidated undrained triaxial test data is presented in Figure 14. These data were also reduced with an assumed sensitivity of 2. As at Site XIV the penetrometer data from each test are consistent with each other and also consistent with the moderate penetration achieved. In addition, they compare favorably to both unconsolidated undrained triaxial shear and mini-vane data. However, these latter data may be below in-situ values because of sample disturbance (the sampler was driven with a hammer).

Site XVI, San Pedro Bay

This site was in San Pedro Bay off the Southern California coast at a water depth of 215 meters (700 feet). Woodward-Clyde Consultants (1979a) performed two tests here with 1.40-kN (315-pound) penetrometers using 80-db sound sources. Both tests gave good penetration records, although some noise was apparent and had to be filtered out. The soil data were gathered with the same methods used at Sites XIV and XV. The soil over the depth of interest varied from a low plasticity clayey silt to a medium plasticity silty clay. The strength profile at this site was determined only with a mini-vane. A comparison of the mini-vane data to penetrometer data is presented in Figure 15. This soil was believed to be clayey because of the distance from shore, and the penetrometer data were reduced with an assumed sensitivity of 3. The penetrometer strength profiles are in remarkably good agreement with each other, but the strengths seem somewhat high for the moderate penetrations achieved. The mini-vane data are considerably lower than the penetrometer data. This may be due in some degree to the fact that the soil samples were recovered by hammering a sampler out the end of a drill string and because the sensitivity used in reducing the penetrometer data was incorrectly assumed. The core data indicated a sensitivity of 2.

Site XVII, Santa Barbara Channel

Two tests were performed by Woodward-Clyde Consultants (1979b) at this site off the Southern California coast in 95 meters (310 feet) of water. Both tests used 1.40-kN (315-pound) penetrometers with 80-db sound sources. The weather was very poor for these tests. During the first test the signal was not recorded because of an error in setting up a tape recorder. On the second test the penetrometer fouled in a lift line and pulled that line with it to the seafloor, thereby sharply reducing the terminal velocity of the penetrometer. No discernible penetration event was found in the data, suggesting a hard seafloor of unknown strength. A boring record of the site indicated dense, nonplastic sandy silt. No data are presented because of the poor quality of the penetrometer record.

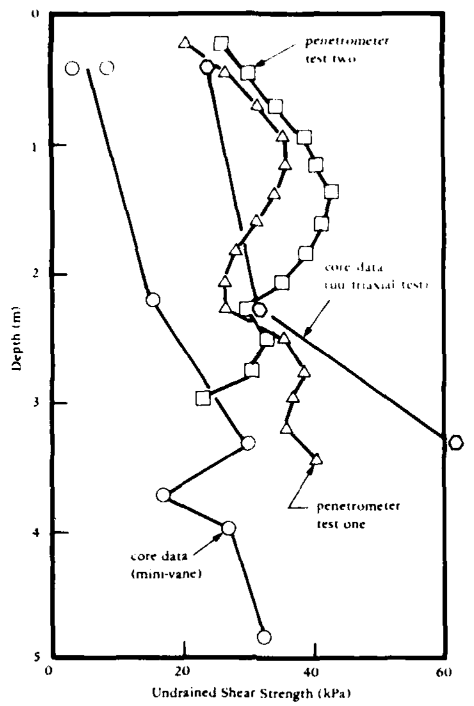

Figure 13. Comparative undrained shear strength data at Site XIV, San Pedro Bay, sandy silt to clayey silt.

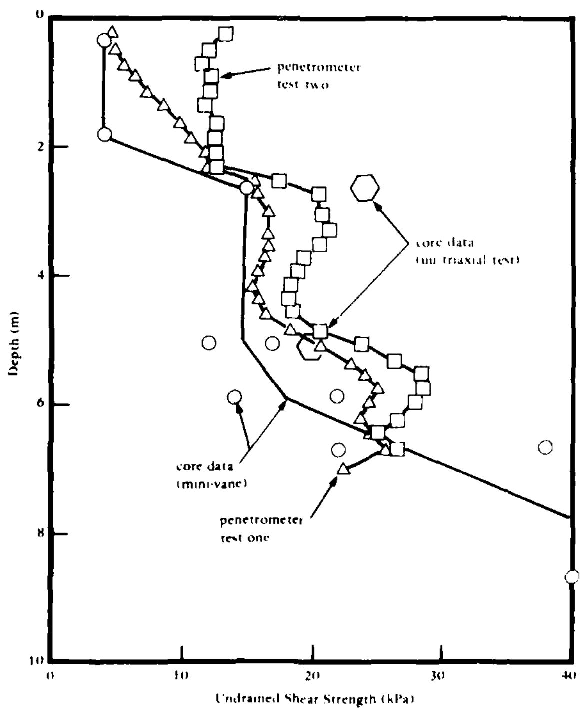

Figure 14. Comparative undrained shear strength data for Site XV, San Pedro Bay, clayey silt.

Site XVIII, Santa Barbara Channel

This site was off the Southern California coast at a water depth of 55 meters (180 feet). Woodward-Clyde Consultants (1979b) performed two tests with 1.40-kN (315-pound) penetrometers with 80-db sound sources. Sea conditions were rough. The penetrometers were deployed by throwing them over the side to avoid the problems encountered at Site XVII. Only fair recordings were obtained. Samples were recovered from this site by driving a Shelby tube sampler out the end of a drill string. The soil was found to be a soft to firm, slightly plastic, silty clay over the soil depth of interest. Of the various types of shear data acquired from the sampler, only mini-vane data and the fall cone are given for comparison to the penetrometer data in Figure 16. These data were representative of the other data. The penetrometer data were reduced with an assumed sensitivity of 2 because the soil was believed to be nonclayey. This is not a bad assumption for this soil because it had a liquidity index of about 0.5 indicating it is not easily disturbed. The penetrometer strength profiles have a similar shape but do not agree well with each other or with the available data; however, the fall cone data on the core sample do indicate a strength of about 100 kPa at 3 meters, which agrees better with the second penetrometer test. The most reliable aspect of the penetrometer data is that penetrations were less than 2 meters (7 feet), indicating a hard seafloor. This is not reflected by the mini-vane data, but that could be because of sample disturbance from coring (the sampler was hammered into the sediment).

Site XIX, Indian Island

Site XIX was located near Indian Island in the northern portion of Puget Sound, Wash., at a water depth of 30 meters (100 feet). Two 1.40-kN (315-pound) penetrometers with 80-db sound sources were deployed, but no data were recorded. What went wrong was never determined. Both sound sources were operating properly and so was the receiver.

Site XX, Caribbean Sea

This site, in 3,730 meters (12,230 feet) of water, was located about 100 km (60 miles) south of Haiti. Two tests were performed here with 1.40-kN (315-pound) penetrometers using 80-db sound sources. A good signal from each test was recorded. A 64-mm- (2.5-inch-) diam piston core 4 meters (13 feet) long was taken with a 100% recovery ratio. Mini-vane tests were conducted aboard the ship. The soil was a firm, fine-grained (clay-sized) calcareous ooze (carbonate content of about 52%). It was apparent when sectioning the core and performing mini-vanes that the samples disturbed easily and that a procedure other than the mini-vane would be necessary to estimate the in-situ strength profile. The method used was the one outlined in the TEST PROGRAM AND PROCEDURES section. The penetrometer data were reduced with an assumed sensitivity of 4 because the ooze was fine-grained. A comparison of the penetrometer- and triaxial-test-derived strength profiles is shown in Figure 17. The data are in good agreement over the upper 2.5 meters (8 feet), but below that depth the penetrometer tests indicate a stronger soil than the laboratory-derived strength profile. The high

strengths indicated by the penetrometer are consistent with the modest penetration achieved. No similar hard layer was found in the core. It should be mentioned that the core was taken several miles from the penetrometer drop points.

Site XXI, Caribbean Sea

This site was about 160 km (100 miles) southwest of Jamaica at a water depth of 1,130 meters (3,710 feet). Two 1.40-kN (315-pound) penetrometers with 80-db sound sources were dropped here and good signals from each were recorded. A 64-mm- (2.5-inch-) diam piston core 3.4 meters (11 feet) long was taken with a 61% recovery ratio. The soil was a sensitive, soft calcareous ooze (carbonate content of 74) composed of primarily clay-sized particles. Mini-vanes were performed but thought too inappropriate. Therefore, the in-situ strength profile was estimated as described for Site XX. The penetrometer data were reduced with an assumed sensitivity of 4. A comparison of the penetrometer- and triaxial-test-derived strength profiles is shown in Figure 18. The agreement was good above 4 meters, but poor below that depth. The strength profiles are consistent with the moderate penetration obtained.

Site XXII, Caribbean Sea

Two penetrometers were tested at this site in 700 meters (2,300 feet) of water about 220 km (140 miles) south of Jamaica. Both penetrometers weighed 1.40-kN (315-pound) and had 80-db sound sources. On the recordings of the data from both of these tests a sharp drop in penetrometer velocity at a depth of about 3 meters (10 feet) was noted. A 64-mm- (2.5-inch-) diam piston core 3.6 meters (12 feet) long was taken with an 80% recovery ratio. The core was a firm, but easily disturbed, calcareous, fine-grained soil. The carbonate content was about 54%. The same procedure used for Site XX was used to estimate an in-situ strength profile. A comparison of this laboratory-derived strength profile to the penetrometer strength profiles is shown in Figure 19. The agreement between the penetrometer- and laboratory-derived profiles is not good. However, the low strengths of the laboratory-derived profile are not consistent with the modest penetration obtained, while the higher strengths in the penetrometer profiles are.

Site XXIII, Caribbean Sea

This site was in 1,800 meters (6,170 feet) of water 290 km (180 miles) south of Jamaica. Two 1.40-kN (315-pound) penetrometers with 80-db sound sources were tested here. Good signals were received and recorded. A piston core 5.5 meters (18 feet) long and 64 mm (2.5 inches) in diameter was taken with a 90% recovery ratio. The soil was a soft, easily disturbed, calcareous ooze primarily composed of clay-sized grains. The carbonate content was about 51%. Because of the sensitive nature of the soil, the procedure used for Site XX was used to estimate the in-situ strength profile. A comparison of this profile to the penetrometer data (reduced with an assumed sensitivity of 4) is provided in Figure 20. The comparison of data at this site is good, with the penetrometer indicating a slightly lower strength profile than the laboratory-derived strength profile.

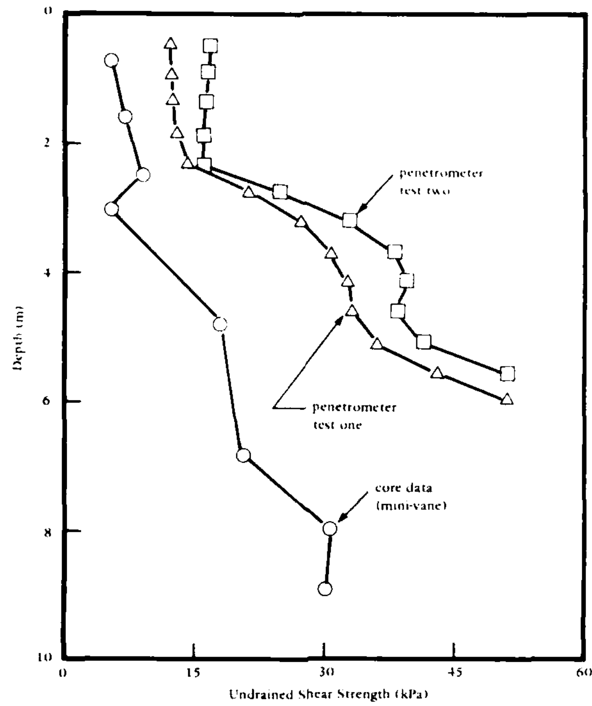

Figure 15. Comparative undrained shear strength data at Site XVI, San Pedro Bay, clayey silt to silty clay.

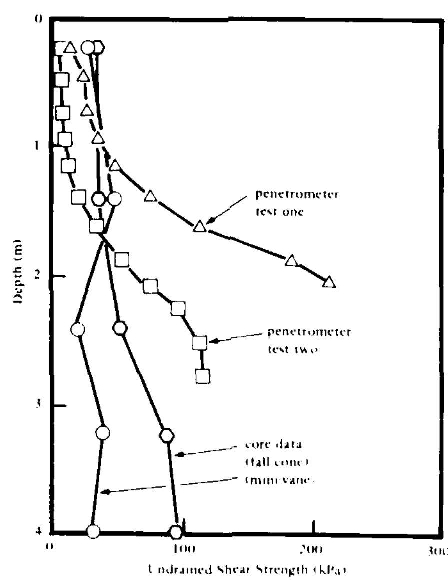

Figure 16. Comparative undrained shear strength data at Site XVIII, Santa Barbara Channel, firm silty clay.

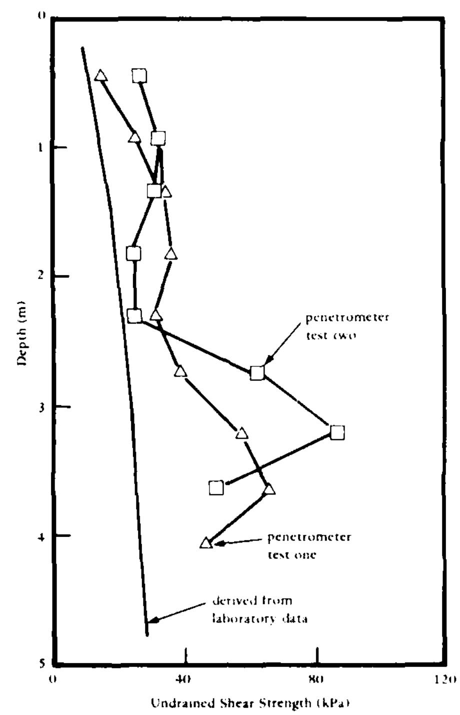

Figure 17. Comparative undrained shear strength data at Site XX, Caribbean Sea, calcareous ooze.

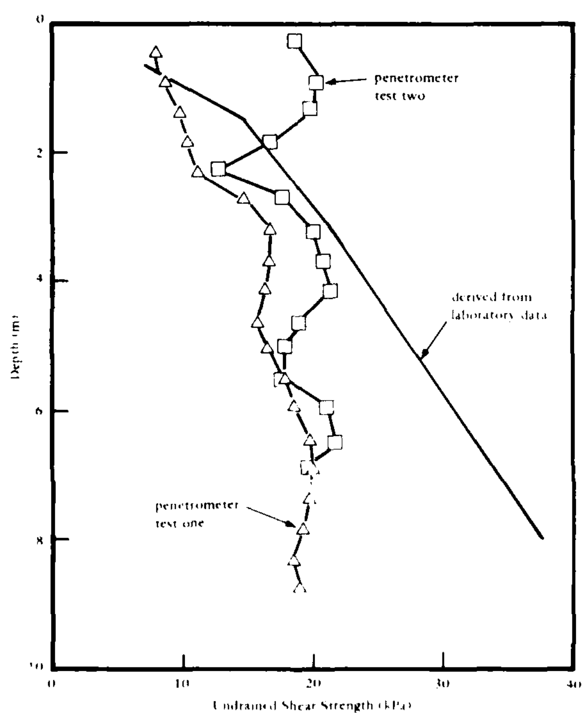

Figure 18. Comparative undrained shear strength data at Site XXI, Caribbean Sea, calcareous ooze.

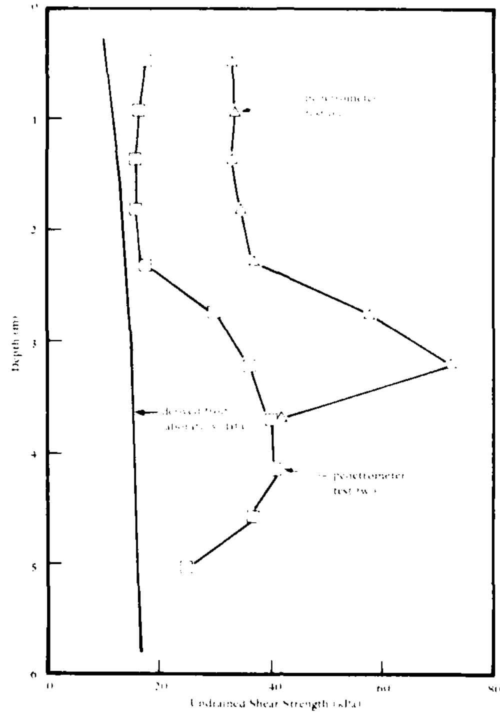

Figure 19. Comparative undrained shear strength data at Site XXII, Caribbean Sea, calcareous ooze.

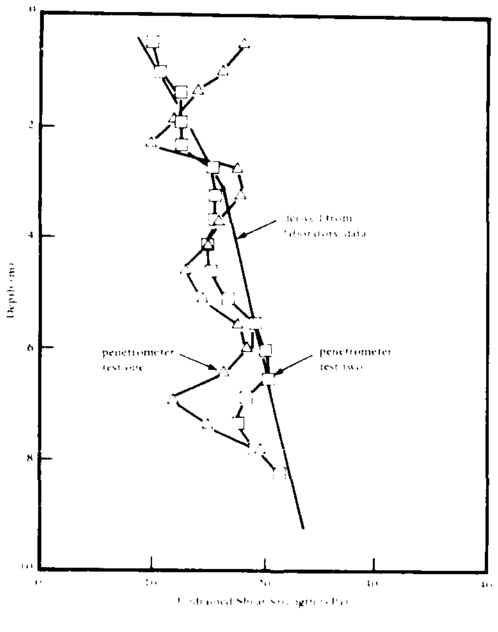

Figure 20. Comparative undrained shear strength data at Site XXIII, Caribbean Sea, calcareous ooze.

Site XXIV, Caribbean Sea

Two 1.40-kN (315-pound) penetrometers with 80-db sound sources were dropped at this site 340 km (215 miles) north-northeast of Panama in 3,690 meters (12,000 feet) of water. Good signals were received and recorded. A 64-mm- (2.5-inch-) diam piston core 5.8 meters (19 feet) long was taken with a 95% recovery ratio. The soil was a sensitive, soft calcareous ooze composed of about 50% clay-sized particles. The carbonate content was 44%. As with the previous four sites, a series of triaxial tests were performed to estimate the in-situ strength profile. A comparison of the laboratory-derived strength profile to the penetrometer data is shown in Figure 21. The penetrometer data were reduced with an assumed sensitivity of 4. The agreement between the laboratory and penetrometer data is good, the penetrometer data indicating a lower strength profile than the laboratory data. The two penetrometer tests are very consistent.

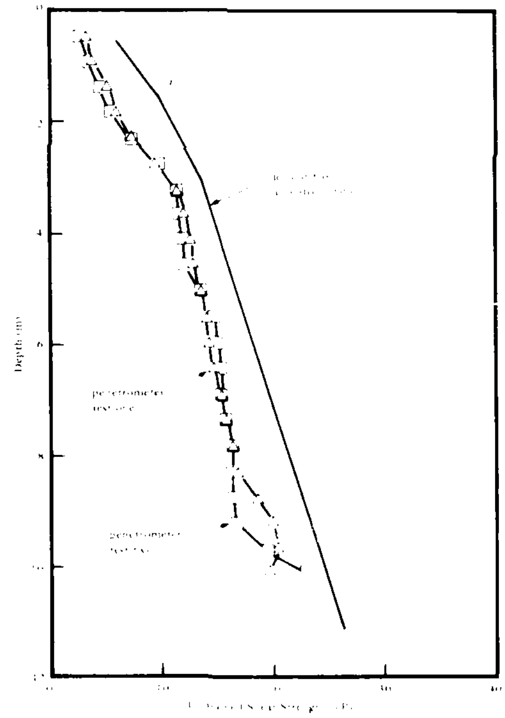

Figure 21. Comparative undrained shear strength data at Site XXIV, Caribbean Sea, calcareous ooze.

DISCUSSION

In general, the penetrometer equipment performed well. The redesigned penetrometer is capable of penetrating to the goal depth of 9 meters (30 feet) and is, theoretically, functional in 6,000 meters (20,000 feet) of water [tested to 4,908 meters (16,090 feet)]. Interpretation of the data usually gave a result that compared reasonably to other available shear strength data. Of the 39 attempted tests reported in this document, sound sources failed to function twice; the signal was received but not recorded (operator error) three times; and noisy, uninterpretable records were obtained twice. The first two 80-db sound sources used were faulty. The problem was found and corrected. In 29 following tests with 80-db sound sources no failures were experienced. Of the tests where penetrometer data did not compare favorably to other available strength data no pattern emerged; that is, the penetrometer was not consistently higher or lower than the data used for comparison.

The experimental 90-db sound sources previously reported by Beard (1977) and those reported here worked very well. When the design was changed to reduce costs, some problems were encountered but overcome (e.g., the oil-filled boot was replaced by a cast rubber-like compound after testing at Site IX and the faulty transistor replaced when testing at the Gulf Stream Outer Ridge, Sites XI, XII, and XIII). After these changes were incorporated, problems with the sound sources were essentially eliminated. The acoustic output of the new source seems adequate for deep ocean operation, having been used successfully in 4,908 meters (16,090 feet) of water. It was calculated that only 2 db more output is required to operate in 6,000 meters (20,000 feet).

The hydrophone performed without problems throughout the test program.

The receiver performed well. Several times the discriminator caused problems, which were usually manifested as noise and signal dropouts on the discriminator output (the direct current analog of the penetrometer velocity.) This signal is the one digitized for analysis to determine soil strength. After repair, the receiver worked correctly. The discriminator can be readily removed and replaced by a spare.

As displayed in the figures comparing strength profiles based on the penetrometer data to other conventionally acquired data, the Doppler penetrometer is capable of providing a reasonable estimate of the undrained shear strength profile. Occasionally the comparisons are poor, but it is not possible to know which data are in error as "ground truth" data are virtually impossible to acquire. The data indicate that the penetrometer strength profiles are more representative of conventionally acquired profiles in clayey soils than in other soils. Strength profiles determined from penetrometer data compared reasonably well to strength profiles developed from triaxial shear tests for calcareous ooze sediments. There is no general trend toward penetrometer-derived strength profiles being consistently higher or lower than profiles derived from conventional methods. Nor is there such a trend when the data are separated by sediment type or strength level. This implies that the errors in the data and method of reducing the data are fairly random.

Beard (1977) compared penetrometer strength profiles to strength profiles acquired by in-situ vane shear testing and laboratory vane shear testing on large-diameter stationary piston corers (core tube pushed into seafloor with a bottom-resting platform) and large-diameter gravity corer samples. These comparative data were of high quality (approaching "ground truth"), and it was found that the penetrometer data fell within ±30% of these data. This represents the accuracy of penetrometer strength profiles.

The penetrometer shear strength profiles in this report have not been statistically compared to the shear strength profiles acquired by other means because these other means do not represent "ground truth." It is possible to develop a feel for the repeatability of the penetrometer data. At sites where undrained shear strength profiles were developed from more than one penetrometer test, mean strength values were calculated at arbitrarily selected depths of 2, 4, 6, 8, and 10 meters (6.6, 13, 20, 26, and 33 feet). Each of 62 data points was normalized by its corresponding mean strength, and a standard deviation for these normalized strength values was calculated. The standard deviation was 16% of the mean. Using this value, it can be stated that the envelope enclosing 95% of the penetrometer data has a band width of about ±30% of a normalized mean value.

The data show that the penetrometer gives a reliable overall estimate of the relative strength of a site. It is apparent that if penetrations are less than 3 meters (10 feet), the soil is stiff [s_u > 50 kPa (7 psi)]. For penetrations between 3 and 7 meters (10 to 23 feet), the soil can be classified as medium [s_u = 24 to 50 kPa (3.5 to 7.1 psi)]. When penetration is from 7 to 12 meters (23 to 39 feet), the soil is soft [s_u = 12 to 24 kPa (1.7 to 3.5 psi)]. When penetration exceeds 12 meters (39 feet), the soil is very soft [s_u < 12 kPa (1.7 psi)]. This type of gross estimate of the strength disregards variation of strength with depth or whether a hard layer stops the penetrometer. It is implied that the strength profile (and soil deposit) is uniform.

The data reduction requires one assumption of significance: the value of sediment sensitivity. Parametric studies showed that the errors in the strength profile are greatest when errors in the assumption of sensitivity are made for sediments of low sensitivity (2-3). These errors can be about 30% if a sensitivity of 2 is used when the actual sensitivity is 3. For higher sensitivity sediments, an error in the sensitivity assumption (for example, 4 when the actual value is 5) leads to errors of about 15%. A low sensitivity estimate results in a low strength estimate and vice-versa. The recommended values of sensitivities to assume, given in Table 2, seem to be reasonable judging by the results shown in Figures 6 through 21. This assumption could be avoided only by making a measurement of sensitivity on the sediment. To do this in a way consistent with expedient site evaluation and the concept of an expendable probe would require the sensitivity measurement to be made with the Doppler penetrometer. This might be possible by measuring the nose force and side friction. However, inertial forces might interfere with the measurements, and the electronics and load cells involved would result in a penetrometer too expensive to be expended.

Another difficulty in reducing the data involves selection of the impact point. The worse case is when the data trace is not clean. The difficulty is selecting the point where the velocity data curves away from the constant value just before impact as the penetrometer gradually slows down on entering the sediment. It is possible to "miss," perhaps, the upper 1 meter (3 feet) of sediment. This results in calculating a strength profile that is shifted slightly to higher strength values near the sediment surface. This is not a problem for geotechnical designs requiring deeper sediment data, such as a propellant-embedded anchor, and this difficulty is significantly lessened in stiffer soils. For soils with soft surface layers that are important to define, this difficulty can be minimized by designing a penetrometer that decelerates quickly at impact; i.e., a shorter, lighter penetrometer. A penetrometer of this design would sense a much larger nose force per unit of penetrometer mass than would a long slender penetrometer and hence, would decelerate quicker. However, it would not penetrate nearly as deep as a long slender penetrometer. Alternately, it might be possible to invent a sediment surface detection feature for the penetrometer that would be in keeping with the concept of expandability and that could be integrated into the Doppler instrumentation.

CONCLUSIONS

1. The Doppler penetrometer data can be reduced to provide a reasonable estimate of the undrained shear strength profile determined by other conventional methods (typically mini-vanes performed on cores). The Doppler penetrometer data most closely duplicate the conventional strength profiles in clayey sediments. The Doppler penetrometer data do not tend to be generally higher or lower than an undrained shear strength profile determined by more conventional methods.

2. Nine meters (30 feet) of penetration is achieved in soft sediments with the new, smaller Doppler penetrometer.

3. The penetration depth of Doppler penetrometer gives a good indication of the average seafloor undrained shear strength.

4. The new 80-db sound source has operated at water depths to 5,000 meters (16,000 feet), and source level measurements and theory indicate that sufficient output is available to operate at 6,000 meters (20,000 feet).

5. The recommended sensitivity values to assume for various sediment types appear reasonable and will result in a good estimate of the in-situ undrained shear strength profile.

6. The difficulty in detecting the point of impact in the data is not a serious problem except in soft sediments and when the data trace is noisy. In this case, up to 1 meter (3 feet) of the surface sediment may be "missed".

7. The new 80-db sound source is reliable, having functioned properly in all tests after some initial problems were corrected. The receiver and hydrophone are reliable with the exception of the plug-in discriminator circuit in the receiver.

RECOMMENDATIONS

1. The Doppler penetrometer should be used as an expedient site investigation tool to provide an assessment of sediment strength. A manual (Beard, 1983) is available that provides instructions for using the penetrometer and reducing acquired data. The Doppler penetrometer is particularly suitable for preliminary site investigations where it is not feasible or cost-effective to core the seafloor and perform laboratory tests on the samples.

2. A spare plug-in discriminator circuit should be available so that if problems arise the faulty circuit can be replaced. Another solution would be to procure a more reliable discriminator circuit.

3. The Doppler penetrometer should be made in different sizes. The penetrometer presented was designed to penetrate fairly deep. Others could be designed for shallower or deeper penetration. The former would allow the strength of near surface sediments to be measured more accurately.

4. Development of a sediment surface detection feature for the Doppler penetrometer should be undertaken.

5. The Doppler penetrometer instrumentation system should be used in other applications; for example, waste cannister disposal studies, where penetration depth or related data are required.

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